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TECHNICAL NOTE
D-143

EFFECTS OF FLIGHT SIMULATOR MOTION ON PILOTS'

PERFORMANCE OF TRACKING TASKS

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A-324

SUMMARY

The effect of motion of a flight simulator on pilots' performance of a tracking task has been investigated by comparing the air-to-air tracking performance of two pilots in flight, on a motionless flight simulator, and on a flight simulator free to roll and to pitch. Two different attack displays were used.

It was found in tracking a maneuvering target that: the results from the moving flight simulator resembled the results from flight much more than did those from the motionless simulator; and that in flight the conventional circle-dot display was superior to a drone display. For simpler tracking tasks it was not possible to detect these differences.

INTRODUCTION

In the design of cockpit-instrument displays flight simulators are used extensively for preliminary studies and for much of the advanced development. Yet, little is known about the differences in pilots' tracking performance between actual flight and simulated flight. In references 1 and 2 are reported studies of pilots' tracking performance in flight and in a motionless flight simulator. In these studies two different radar-target tracking displays were used in air-to-air lead-collision attacks against a nonmaneuvering target. The simulator tests (ref. 1) indicated moderately better tracking with a "drone" display than with a "circle-dot" display. (The two displays are sketched in figure 1 and are described in some detail in the next section.) The flight tests, as interpreted in reference 2, did not disagree with the simulator tests, though they were inconclusive.

Ames Research Center personnel, who have accumulated considerable experience in studying radar-target tracking problems (refs. 3 and 4), felt that flight tests of the two displays in attacks against a maneuvering target, instead of a nonmaneuvering target, would show more clearly any important differences. In addition, and of more fundamental interest, repetition of the tests on a flight simulator free to pitch and to roll, and again on a motionless simulator, would provide data which on comparison with flight data might yield an estimate of the effects of simulator motion on pilots' performance of a tracking task.

Therefore, the experiment reported here was undertaken. Two Ames test pilots used both the circle-dot and the drone displays in lead-collision attacks against a nonmaneuvering target and in pursuit attacks against both a nonmaneuvering target and one executing a level, 1.5 g turn. Tests were performed in flight, in a flight simulator free to pitch and to roll, and in the same simulator with no motion.

A very brief discussion of the results of this study, as well as the results of several other Ames studies which afforded comparisons of flight and simulator results, is presented in reference 5.

EQUIPMENT AND TESTS

Flight Studies

The attacker airplane was an F-86D interceptor (fig. 2) equipped with an E-4 radar fire-control system which is described briefly in references 3 and 4 and in detail in references 6 and 7. The target airplane (an F-84F, an F-86A, or an F-86F) was equipped with two rearward-pointing radar corner reflectors mounted in external fuel tanks.

The two test displays, the drone and the more conventional circle dot (refs. 1 and 2), are shown in figure 1. In the circle-dot display a fixed reference circle (analogous to a fixed iron gunsight ring), a moving target dot, and a stabilized horizon line are presented on the oscilloscope face. The target dot is displaced from the center of the fixed circle according to the instantaneous position of the target relative to the attacker. The attacker pilot flies his airplane in a manner which will keep the target dot at the center of the fixed circle (much as he would track a visible target, with zero lead angle, with a fixed iron gunsight ring). The horizon line of the circle-dot display behaves essentially the same as the horizon line of an attitude gyro, and from it the pilot can estimate the bank and pitch angles of his airplane. In the drone display the target symbol, a dash, is fixed at the center of the oscilloscope face. The attacker symbol is an inverted "T," the drone. This drone is displaced from the fixed target symbol according to the instantaneous position of the attacker relative to the target. The attacking pilot flies his airplane in such a manner as to keep the drone superimposed on the fixed target symbol. In addition, the drone is made to rotate according to the attacker bank angle, which is presented in the display as the angle from a line across the center of the oscilloscope face and parallel to the airplane lateral axis to a line through the drone "wings." Pitch angle is not shown.

A-324

All tests were run with both the target and attacker at 30,000 feet altitude, 0.70 Mach number. For the pursuit-tracking task the target flew straight and level for 60 seconds then executed a 1.5 g level turn for 60 seconds. A sketch of the maneuver is shown in figure 3. All turns were made to the right. The attacker tracked the target from astern at a nominally constant range of 1000 yards. The test conditions chosen were those which resulted in least radial gun line wander in the experiment of reference 3. Range and projectile time, two of the fire-control-system computer parameters, were fixed respectively at 1000 yards and at 4 seconds. (The rationale of this procedure is explained in ref. 3.) The computer was also biased so that the attacker flew about 100 feet below the target in order to avoid its wake. This did not adversely affect the attacker pilot's tracking performance.

Lead-collision attacks were begun with the flight path of the attacker nominally 90° from the flight path of the target. The fire-control-system radar locked on at ranges between 12 and 15 miles. In lead-collision attacks, range and time to go to impact vary continuously through a run according to the varying geometry of the attack.

Continuous motion picture records of a test run were obtained by photographing the tracking display with a 16mm GSAP camera. The camera was mounted so that it did not interfere with the pilot's view of the display.

Of the two pilots who made the test runs, one, pilot A, had had a great deal of experience with the circle-dot display and the E-4 fire-control system, for he had flown almost all the tests reported in references 3 and 4. Before this experiment he was given a very brief introduction to the drone display on the motionless flight simulator used for the tests of reference 1. However, he had no previous flight experience with the drone display. Pilot B had never used an airborne radar fire-control system with an oscilloscope display.

There are eight combinations of pilots, displays, and tasks. The number of data runs for each combination is given in the following table. The order in which each pilot performed the four display-task combinations is the order in which they are listed.

Display	Task	Number of data runs
	Pilot A	
Circle dot	Pursuit	14
Drone	Pursuit	12
Drone	Lead collision	23
Circle dot	Lead collision	26
	Pilot B	
Drone	Pursuit	27
Drone	Lead collision	18
Circle dot	Lead collision	27
Circle dot	Pursuit	42

Simulator Studies

Figure 4 is a photograph of the flight simulator used for the experiment. The cockpit is mounted within a set of two gimbals; the inner gimbal axis is coincident with the cockpit lateral axis, and the outer gimbal axis is coincident with the longitudinal axis when the inner gimbal angle is zero.

Figures 5 and 6 show the interior of the cockpit. The cathode ray tube, on which the tracking display was presented, is identical to the one which was in the test airplane. Of the controls, which can be seen in both figures, only the control stick was operative. Though there was a throttle grip, no thrust control was provided in the simulation since the added complication was unwarranted for these tests. In addition the rudder pedals were made immovable and the sideslip angle was fixed at zero since, in flight, the pilots used the rudder as only a sideslip nulling device. Both these simplifications were entirely acceptable to the pilots.

A simplified block diagram of the simulation is shown in figure 7. The space geometry, the radar, and the attack computer are identical to those of reference 8. As can be seen by comparing figure 7 of this report with figure 2 of reference 8, the attack coupler and the autopilot of the automatic interceptor simulation of reference 8 were replaced with the corresponding elements of the manual E-4 system. The control loop was then closed with the pilot and the flight simulator. The aircraft equations of motion differ from those of reference 8 only in that the yaw damper was assumed to be efficient enough to keep rate of change of sideslip angle identically zero. This simplification was necessary because of equipment limitations and, as explained in the preceding paragraph, was entirely acceptable to the pilots. The quickening circuit is shown in figure 8. The necessity for quickening and the calculation of the time constants are explained in reference 6. It can be seen in figure 8 that when the display-change switch is in the drone position, one resolution of the error signal is bypassed.

This is because from a display generation standpoint the drone display presents tracking error in a set of pseudo earth coordinates. The circle-dot display presents tracking error in a set of coordinates fixed in the airplane and so the last resolution is necessary.

For both the lead-collision and the pursuit-tracking tasks the speeds of the interceptor and the target were held constant. The initial conditions and the simulated flight path of the target were made to duplicate, as nearly as possible, those of the flight tests. In addition, for the pursuit-tracking task the range from interceptor to target was constrained to be constant and the lead-angle computation was omitted from the attack computer. Since in the flight tests the tail-chase portion of the pursuit task proved to be ineffective as a basis for comparing the displays, the steady turn portion of the simulated pursuit task was preceded by only 15 seconds of steady, straight-and-level tail chase instead of 60 seconds as in flight.

Twelve data runs were made on each of the moving and the motionless simulators for each of the eight combinations of pilot, display, and task. The order in which the runs were made was not predetermined; but it is quite certain that this had no effect on the results. Data were recorded on 16mm film, much the same as was done for the flight tests except that a repeater oscilloscope in the analog computer room was photographed instead of the oscilloscope inside the simulator.

DATA REDUCTION

For the pursuit task the radial tracking error, in inches of displacement of the moving display element from the zero-error position, was read from every tenth frame (every 10/16 seconds) of the 16mm motion pictures of the attack display. For the lead-collision attacks the error was read at integral values between 20 and 4 of the fire-control-system parameter, time to go to impact.

The procedure for data analysis, which was the same for both flight and simulator tests, was devised as follows. In the previous studies of air-to-air tracking performance by interceptor pilots (e.g., ref. 3) the measure of accuracy has been the average value of a set of root-mean-square (rms) tracking errors, one rms error having been obtained for each run from many samplings taken instantaneously through the run. This method of analysis imposes the assumption that the time history of tracking error is essentially a stationary time series - a reasonable assumption for the tail-chase portion and for the steady turn portion of the pursuit task, but an unreasonable assumption for the transition into the turn (and a questionable one for the lead-collision run). Data from the transition were therefore discarded in previous studies. However, in the present study the test pilots' comments indicated that significant results would be found in the transition data. Obviously, it was then necessary that these data be included in the analysis. In order to do this, the complete time history of radial tracking error for one run of the pursuit task was regarded as the experimental unit; and the time scale origin of each unit was taken at the instant the target began transition from straight to turning flight (see fig. 3). Then an estimate of the mean time history for a given set of experimental conditions could be obtained by averaging the error over all the experimental units (time histories) at identical instants of the time scales. In addition, by averaging the squared residual error over all the experimental units, again at identical instants of the time scale, an estimate of the variability which is likely to occur in tracking performance from run to run could be obtained. Mean and variability time histories for the lead-collision attacks were obtained in the same manner as for the pursuit task except that the averaging was done at the integral values of time to go to impact at which the film records were read.

Time histories of the mean error and the variability in tracking performance are presented in figures 9 through 22 for the various test conditions.

RESULTS OF FLIGHT STUDIES

Learning

An attempt was made to establish a learning trend for pilot A with the drone display and for pilot B with both displays. However, the variability in pilot performance from run to run completely masked whatever learning process was taking place.

Differences in Pilots' Tracking Performance Between Displays

Pursuit task.- Figures 9 through 12 show very little difference, in general, between the two displays under the static conditions of the tail-chase portion of the task (negative time). This is the expected result and is in qualitative agreement with the results of references 1 and 2. Pilot B was somewhat better in both average and variability with the circle dot, but not appreciably so. The build-up of error at about -10 seconds in figures 9 and 11 is due to a control reversal made by pilot A during one of his early runs with the drone display. Other than this, he tracked equally well with both displays in the tail chase.

When the target began the transition from steady straight flight to steady turn (time = 0) the average tracking error (figs. 9 and 10) rose to a peak value some 10 to 15 times as high as in the tail chase;

then as the turn stabilized, the error tended to assume a steady value higher than that of the tail chase. Figures 11 and 12 show that the variability followed the same general trend as did the mean error.

The differences which exist between these two displays, at least as reflected in the performance of these two pilots, can be seen in the transition and steady-turn portions of the time histories in figures 9 through 12. For both pilots the peak mean error (figs. 9 and 10) during transition was higher with the drone display; it took several seconds longer for the pilot to reduce the mean error from its peak value to some relatively constant value after the steady turn was established; and this relatively constant value in the turn was higher. In general, the same contrasts are present in the variability time histories, figures 11 and 12, except that pilot B showed somewhat more variability in the transition with the circle-dot display than he did with the drone.

With the exception of the first flight of pilot B with the drone display, the pilots made no errors in turn direction (control reversals) when tracking the target into the turn. Obviously, no such errors should have been expected since the target always turned to the right. However, on his first flight, which was with the drone display, pilot B was not aware that all turns would be made to the right, but believed, rather, that the direction would be random. In his first two runs he misinterpreted the drone display and turned away from the target. By the time he corrected his mistake he had lost the target. Data from those runs were therefore discarded.

The tendency of this pilot, on his first few runs, to make "wrong-way" type errors with the drone display cannot be attributed to habits formed from experience with the conventional radar-tracking display, since he had had none. It is possible that his reactions were conditioned by training and experience in use of the conventional attitude gyro, which presents attitude information in a sense compatible with that of the circle-dot display and opposite to that of the drone display.

Lead-collision attacks.- Time histories of the average tracking errors are plotted in figures 13 and 14 and of the variability in tracking errors in figures 15 and 16. It can be seen that both pilots tracked about equally well on the average (figs. 13 and 14) and with about the same variability (figs. 15 and 16) with either display. These results agree, at least qualitatively, with those of reference 2 in that they demonstrate no definite difference in performance between the two displays. It appears that a lead-collision attack against a nonmaneuvering target, like the tail-chase part of the pursuit task, is not a sufficiently difficult task to bring out latent differences between these two displays.

Differences Between Pilots

Pursuit task.- Figures 9 and 10 show that pilot A was, in general, able to maintain a somewhat lower average tracking error than pilot B was, probably as a result of pilot A's greater experience with the fire-control system. The difference between the pilots was not as great with the drone display as it was with the circle dot, undoubtedly because pilot A had all his previous experience with the circle dot. The largest difference was evident in the transition into the turn of the pursuit task. Figures 9 and 10 show that pilot A kept the average tracking error lower in the transition than did pilot B, particularly with the circle dot. After the turn was stabilized the difference in average error between the pilots was quite small with either display. A comparison of figures 11 and 12 shows again the effect of pilot A's experience with the circle-dot display. He tracked much more consistently in the turn than did pilot B, particularly so during the early part of the turn. On the other hand, with the drone display pilot B was, at least in part, more consistent than pilot A even though B had a somewhat higher average error (figs. 9 and 10).

Lead-collision attacks.- The comments made in discussing the differences between displays in lead-collision attacks apply here also. In figures 13 through 16 no significant difference between the two pilots is evident. It can be concluded that the lead-collision task was, again, not sufficiently difficult to bring out differences.

COMPARISON OF FLIGHT AND SIMULATOR RESULTS

To facilitate the subsequent discussion the flight results of figures 9 through 14 are presented again, in conjunction with the pertinent simulator results, in figures 17 through 22.

Pursuit Task

Figures 17 and 18 afford at least a qualitative comparison of the tracking performance with the airplane, moving simulator, and motionless simulator for each pilot. The figures show that for the moving simulator the shapes and relative magnitudes of the time histories of average tracking error are more nearly like those of flight (though the absolute magnitudes are generally somewhat lower) than are those for the fixed simulator. In fact, on the fixed simulator pilot B tracked somewhat better with the drone display than with the circle dot - a result exactly opposite to that of flight. Figures 19 and 20 show the variability in the pilots' tracking performance on the simulators and in flight. The contrasts here are not as clear cut as for the average errors. In general both pilots were considerably more variable in flight than on either simulator - except for pilot B with the drone display on the fixed simulator. The time histories for pilot A on the moving simulator resemble, at least in shape and in relative magnitude, the corresponding time histories in flight. No similar correlation appears among the three test environments for the variability in tracking by pilot B. He was considerably more variable on the motionless simulator than on the two-degree-of-freedom simulator, and neither simulator time history closely resembles the flight history.

Why tracking performance differs among flight, the moving simulator, and the fixed simulator cannot be deduced from the results of this experiment. It is obvious, though, that for comparing the two displays a fixed simulator gives results entirely different from flight, except for tracking problems approaching the trivial. On the other hand the moving simulator appeared to give results which, at least for average error, could be related to flight.

Lead-Collision Task

Figures 21 and 22 show the average tracking errors for each pilot. The performance on the two simulators is, in all cases, better than that in flight. However, the results do not vary appreciably either between simulators or between displays.

The variability was essentially zero for all simulated cases and therefore no time histories are presented for this parameter in the lead-collision attacks. So it appears that for the essentially static tracking problem of the lead-collision task the motion of the two-degree-of-freedom simulator provided no advantage over the fixed simulator. Just as for comparing the displays in flight, lead-collision tracking was too simple a task to bring out the differences between simulators.

PILOT OPINION

In considering the characteristics of these two displays in the three environments under discussion it might be well to look at them from the pilot's viewpoint. An understanding of this viewpoint could help to explain the statistical differences shown in the data.

The pilot governs his control of an airplane by visual and vestibular cues to achieve the goal of his flight. Through experience some of these cues are not sampled in a conscious manner but contribute in an automatic way to his control inputs. With a motionless flight simulator, all of the pilot's cues are visual except for the motion and forces involved with the control he is using. With the moving simulator used in this investigation, roll and pitch motions and accelerations are available for the pilot's vestibular sensing but other motion cues are not present. The fidelity of the simulation will depend on whether the task given the pilot can be represented to his senses accurately by vision alone or whether some motion is necessary. The relative importance of the motion in different axes may also have a bearing on the simulation of a particular task.

The circle-dot display as described under equipment is a symbolic representation of what the pilot would see if he were looking through the airplane windshield. The artificial horizon provides him with a reference since it remains fixed in space parallel to the natural horizon. From it he reads the pitch and roll attitude of his own airplane by use of the fixed circle in the center of the scope. The moving dot represents the target and shows its relative displacement from the horizon and from his own airplane. It is important to keep in mind that the pilot is flying the fixed circle - his controlled element. In flight, most of the visual cues the pilot uses are given by this display in the same relationships that he sees when performing a visual tracking task. In a simulator free to pitch and roll, it appears that most of the important motion cues are present and the display should present a satisfactory representation to the pilot. With the motionless simulator, however, the artificial horizon moves while the real horizon or earth reference stands still. Not only does this motion disagree with the pilot's sensing of no motion but the artificial horizon rotates and moves in a direction opposite to the pilot's stick rotation and movement. This tends to cause some confusion in the pilot's sensing and can lead to errors usually of control reversals or control inputs opposite to those desired. It appears that the circle-dot display becomes less satisfactory as motion is eliminated from the simulation.

With the drone display used in tracking in flight, the pilot has no pitch information available since his attitude symbol, the drone, shows target error and airplane bank angle referenced to the airplane cockpit. The motion of the drone in roll tends to be confusing since it rotates in space twice as fast as the pilot does and therefore does not agree with some of his motion cues. The drone which must be considered the controlled element is actually governed by two independent inputs, one from the pilot's controls and one from target information. This causes confusion since there is no direct relationship between the pilot's input and movement and the motion of the drone. The same comments generally apply to the use of this display in a rolling and pitching flight simulator. In a ground-fixed simulator, the drone display is an easy one to use. The bank angle of the drone symbol is a direct indication of bank referenced to both the cockpit and to the real horizon. The roll velocity of the drone is a direct function of control input in rate and direction. It appears that the drone display becomes less satisfactory when motion is added to the simulation.

CONCLUDING REMARKS

In order to obtain an estimate of the effect of rolling and pitching motions of a flight simulator on the pilot's performance of simulated tracking tasks, comparative studies of two air-to-air tracking displays were made in flight, on a two-degree-of-freedom flight simulator, and on a motionless flight simulator. A drone display and a circle-dot display were used for two tracking problems: a pure pursuit task, and a lead-collision attack. From an appraisal of the results the following can be said.

A-324

For flight simulator studies of cockpit displays it appears that a motionless simulator should not be used. Further, the results of studies on a simulator which provides the pilot with motion stimuli should be extrapolated to flight with reservation.

In flight the drone display offers no improvement in tracking accuracy over the conventional circle-dot display under the essentially static conditions of attacks against a nonmaneuvering target. For pursuit attacks against a maneuvering target the circle-dot display is appreciably superior in both average tracking error and in variability of tracking error.

Work should be done to establish, more comprehensively, the relationship between motion stimuli and the degree of realism of a simulated problem as measured by the similarity between pilots' performance in the airplane and in the flight simulator.

Ames Research Center
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REFERENCES

1. Roscoe, S. N., Wilson, K. V., and Deming, H. D.: Manual Steering Display Studies. II. The Transition of Skilled Interceptor Pilots From the E-Series Display to the Moving Airplane Display. Tech. Memo. 381, Hughes Aircraft Co., Culver City, Calif., Nov. 1, 1954.

2. Anon.: Interim Engineering Report on the Study of Interceptor Fire Control System Improvements. Rep. 507-03-P, Hughes Aircraft Co., Culver City, Calif., 15 Dec. 1955.

3. Turner, Howard L., Rathert, George A., Jr., and Heinle, Donovan R.: Tracking Performance of a Swept-Wing Fighter With a Director-Type Radar Fire-Control System and Scope Presentation. NACA RM A57J01, 1958.

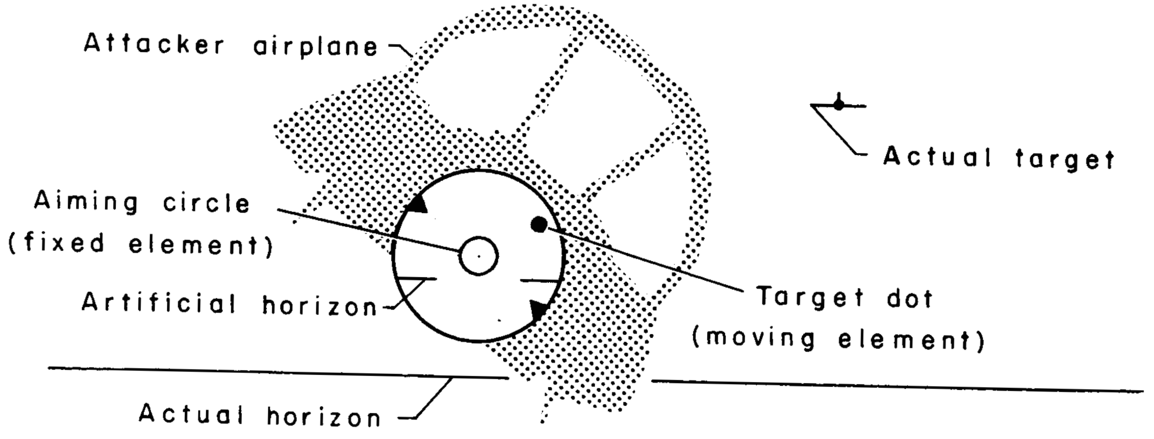
4. Turner, Howard L., and Heinle, Donovan R.: A Flight Study of the Effects of Noise Filtering in the Attack Display on the Pilot's Tracking Performance. NACA RM A58E21, 1958.

5. Rathert, George A., Jr., Creer, Brent Y., and Douvillier, Joseph G., Jr.: Use of Flight Simulators for Pilot-Control Problems. NASA MEMO 3-6-59A, 1959.

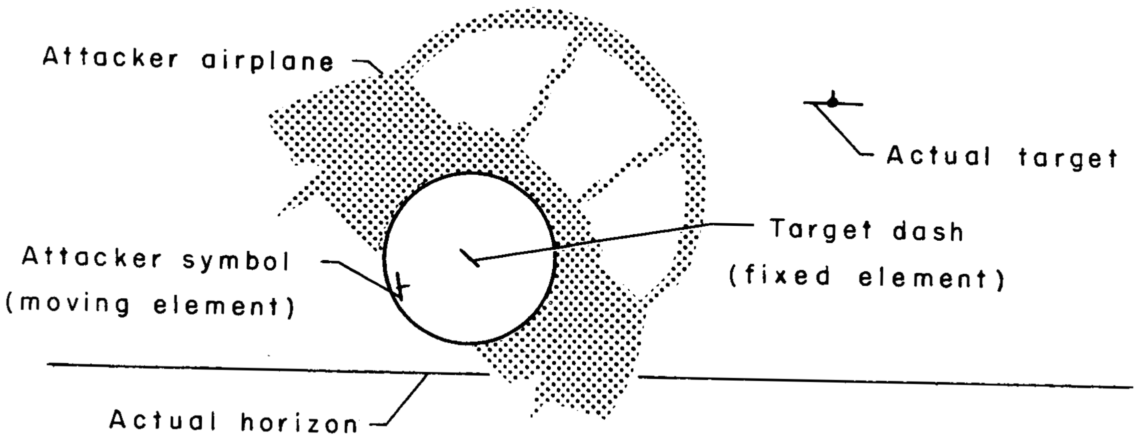
6. McVey, Bruce D.: An Electronic Rocket Fire-Control Computer, Type AN/APA 84., Tech. Memo. No. 314, Hughes Aircraft Co., Culver City, Calif., July 1, 1953.

7. Anon.: Handbook of Service Instructions, Fire Control System Type E-4. Tech. Order CO 11-70ABD-2, Hughes Aircraft Co., Culver City, Calif., July 1, 1953.

8. Triplett, William C., McLean, John D., and White, John S.: The Influence of Imperfect Radar Space Stabilization on the Final Attack Phase of an Automatic Interceptor System. NACA RM A56K19, 1957.



(a) Circle-dot display.



(b) Drone display.

Figure 1.- The two test displays in identical tracking situations.

A-18859

Figure 2.- The test airplane.

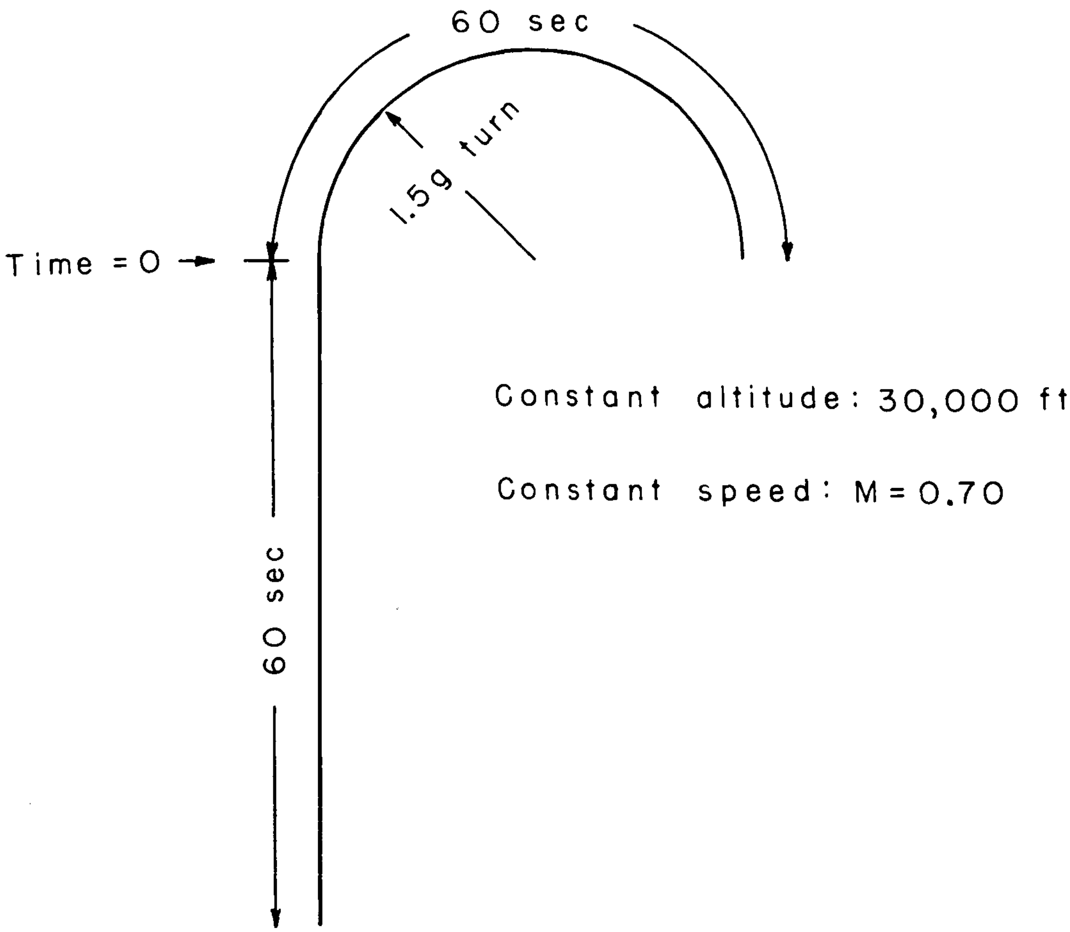


Figure 3.- The target maneuver for the pursuit task.

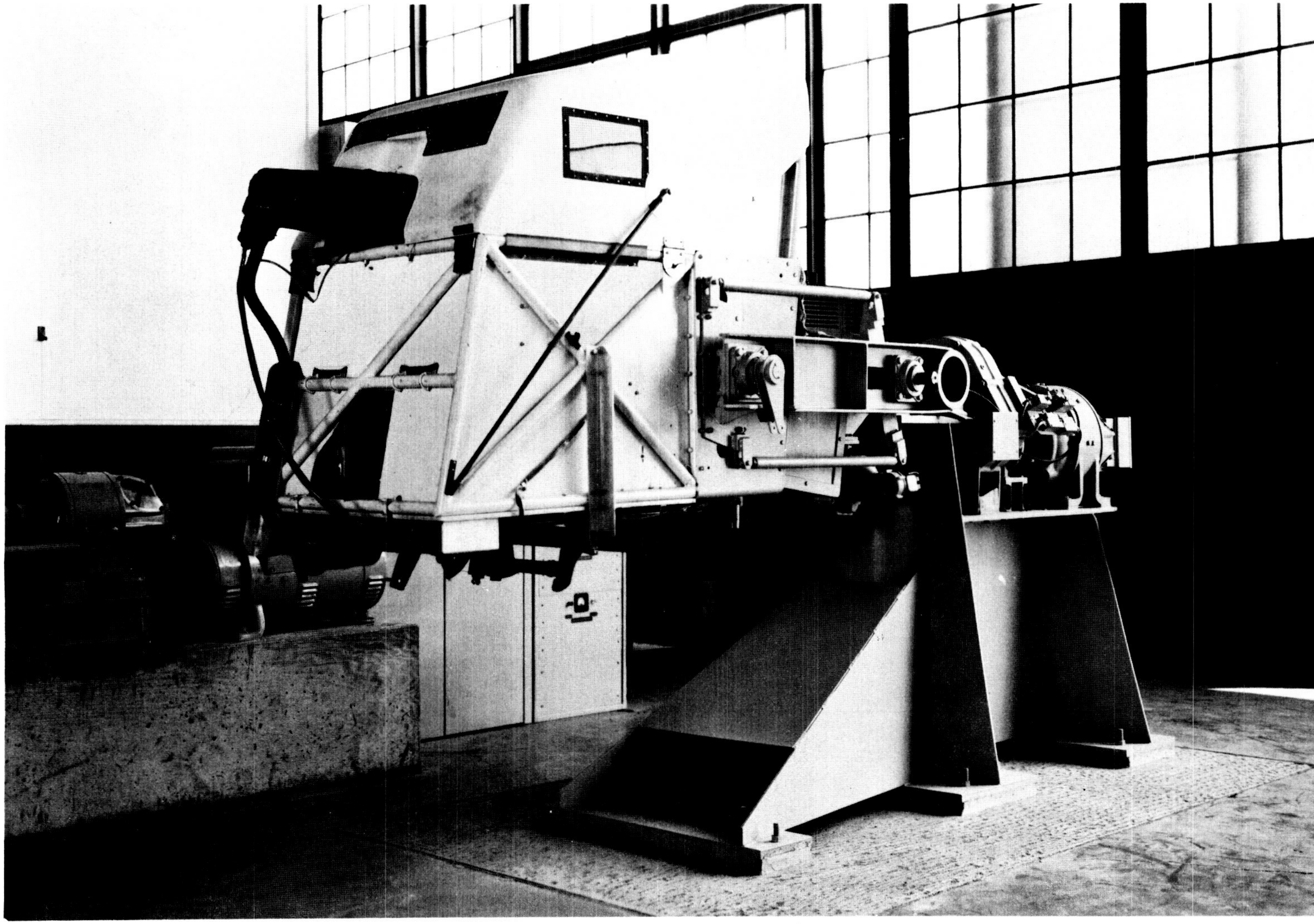


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Figure 4.- The flight simulator used for these tests.

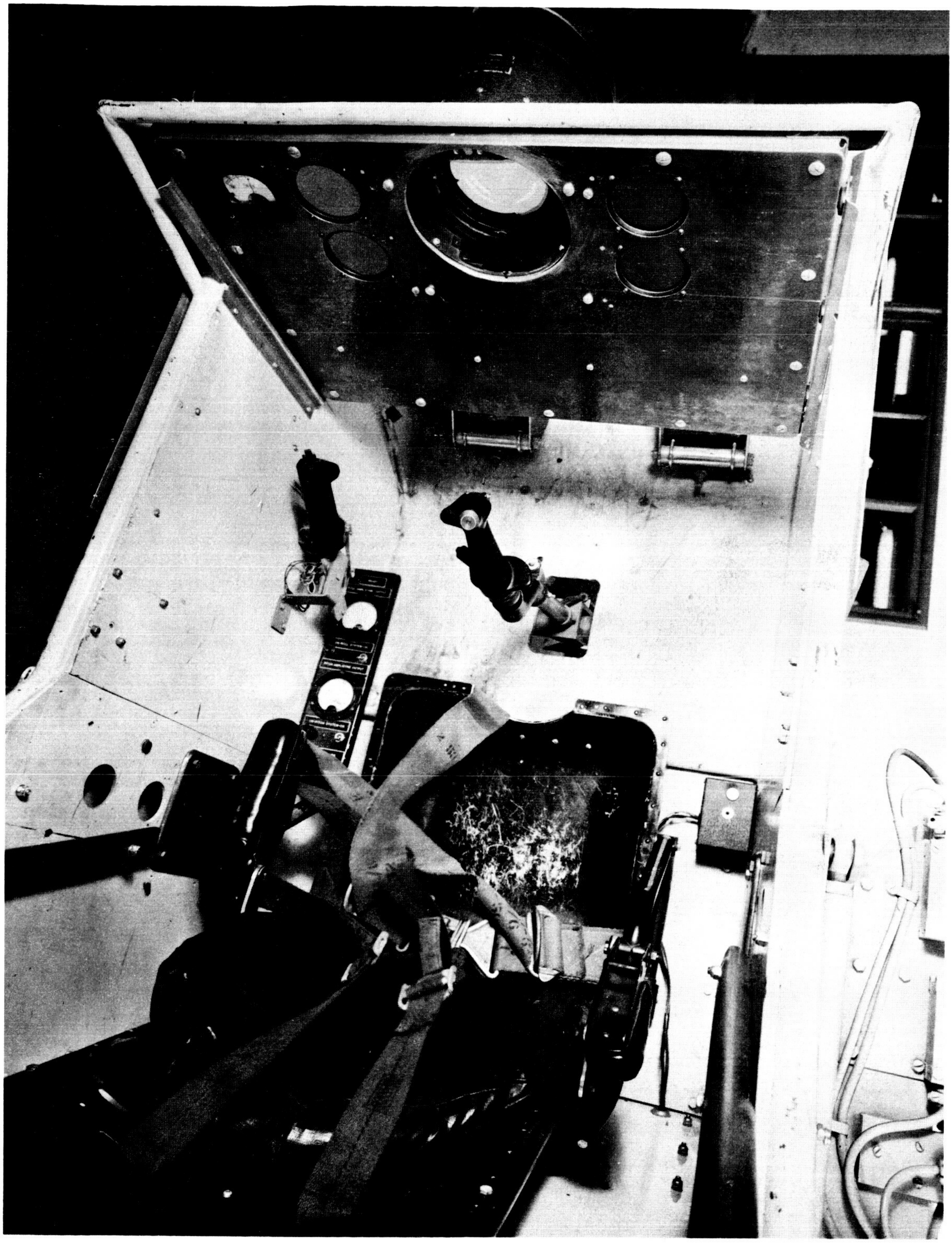

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Figure 5.- The interior of the simulator cockpit.

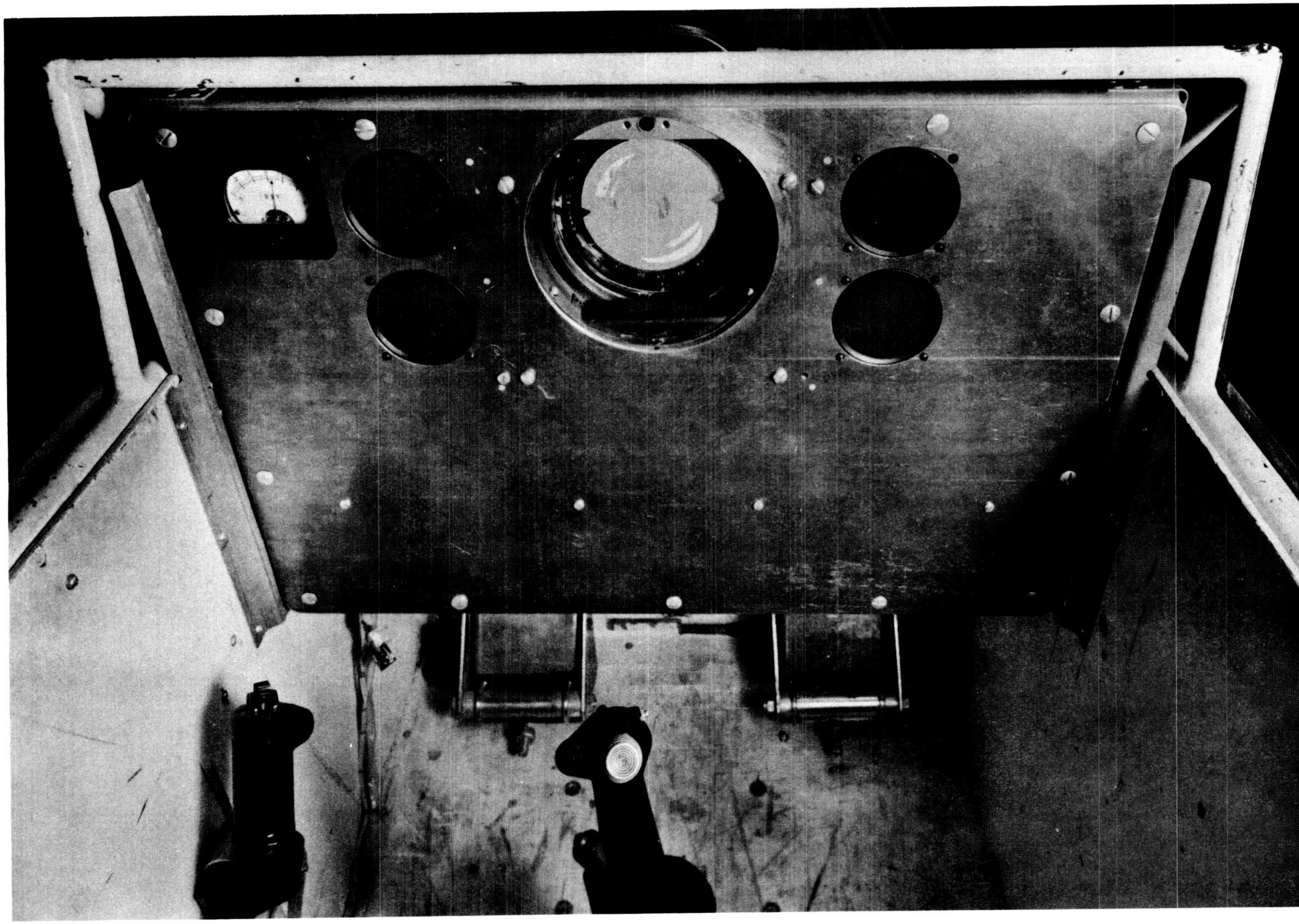

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Figure 6.- The simulator instrument panel.

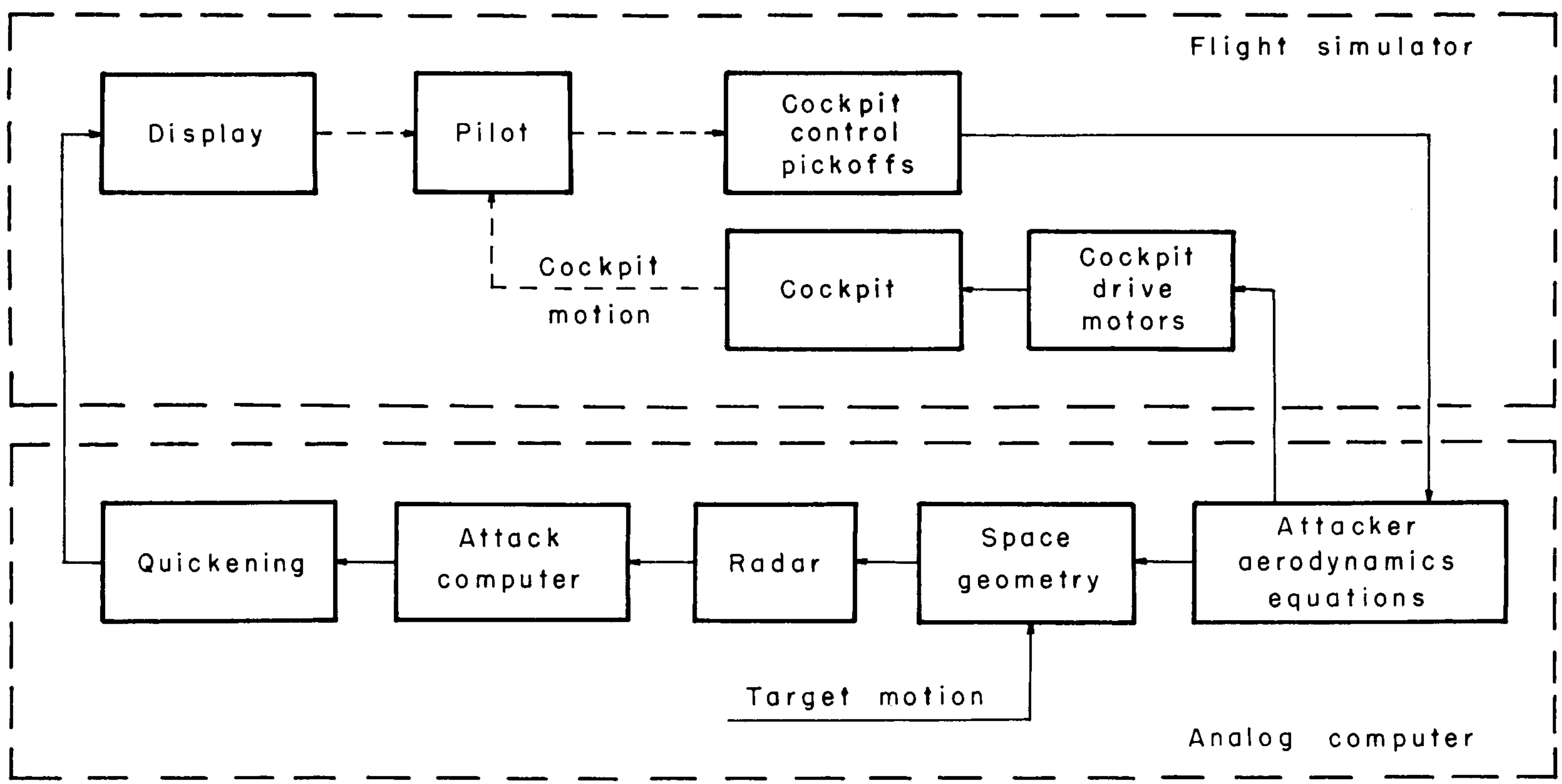


Figure 7.- Simplified diagram of the analog computer circuits and the flight simulator.

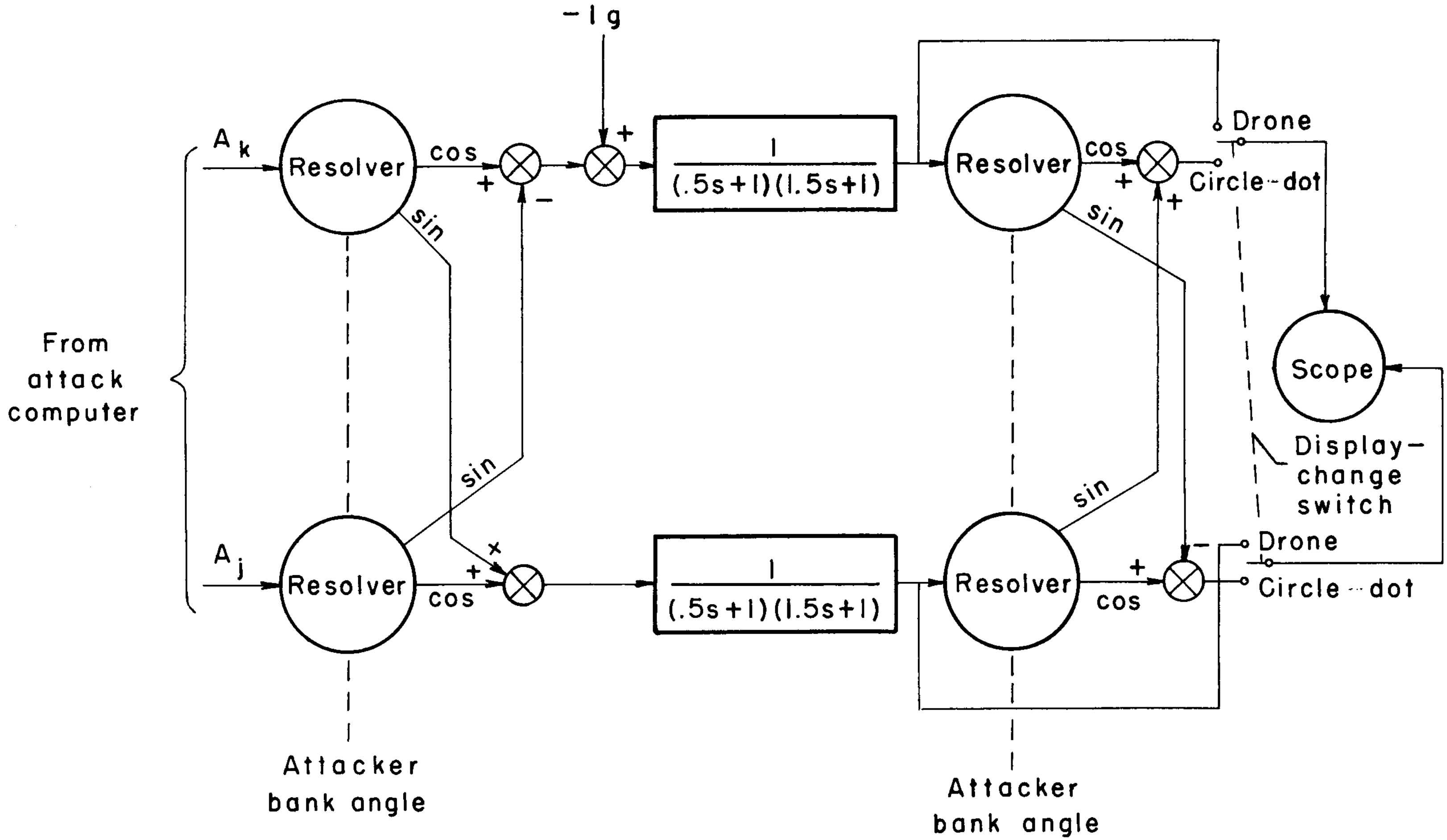


Figure 8.- Block diagram of the quickening circuit.

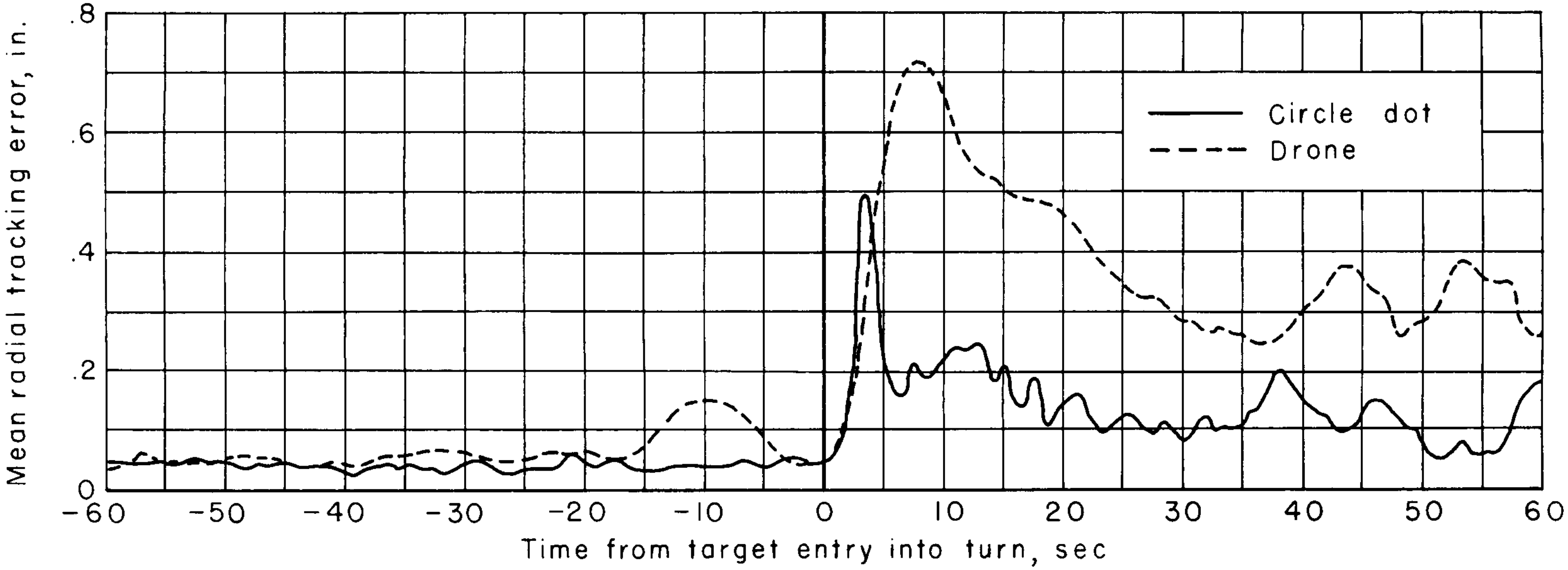


Figure 9.- Time histories of mean radial tracking error during the pursuit task in flight; pilot A.

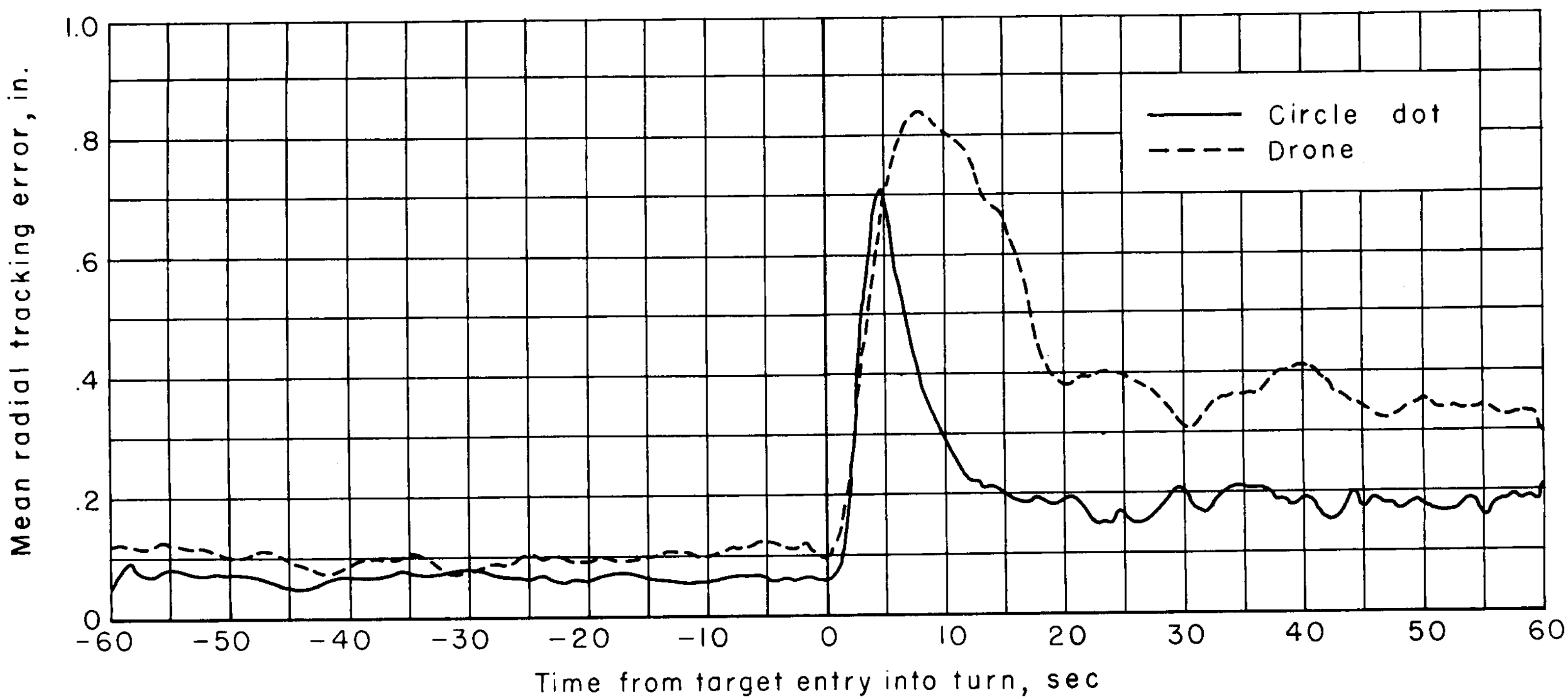


Figure 10.- Time histories of mean radial tracking error during the pursuit task in flight; pilot B.

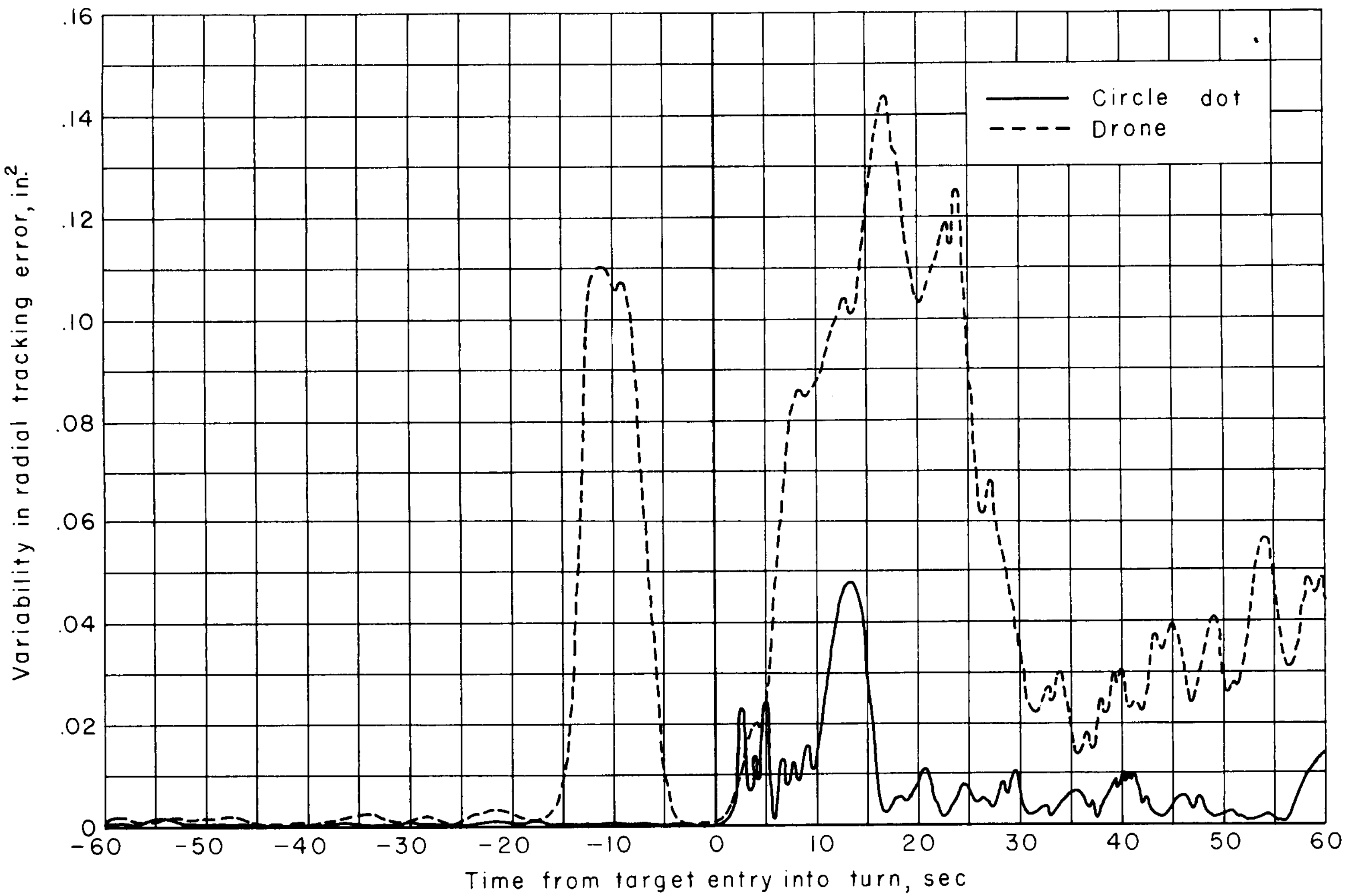


Figure 11.- Time histories of variability in radial tracking error during the pursuit task in flight; pilot A.

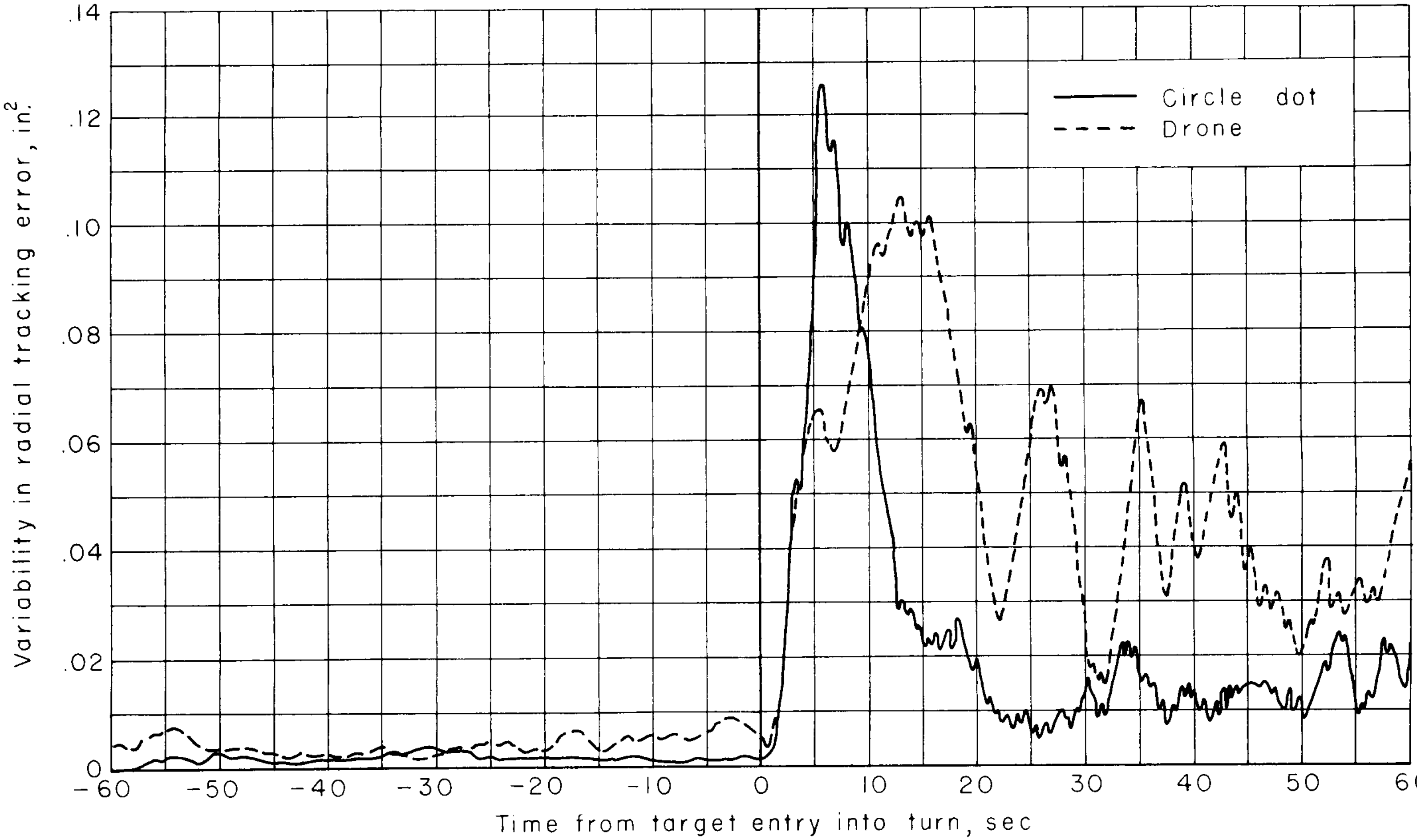


Figure 12.- Time histories of variability in radial tracking error during the pursuit task in flight; pilot B.

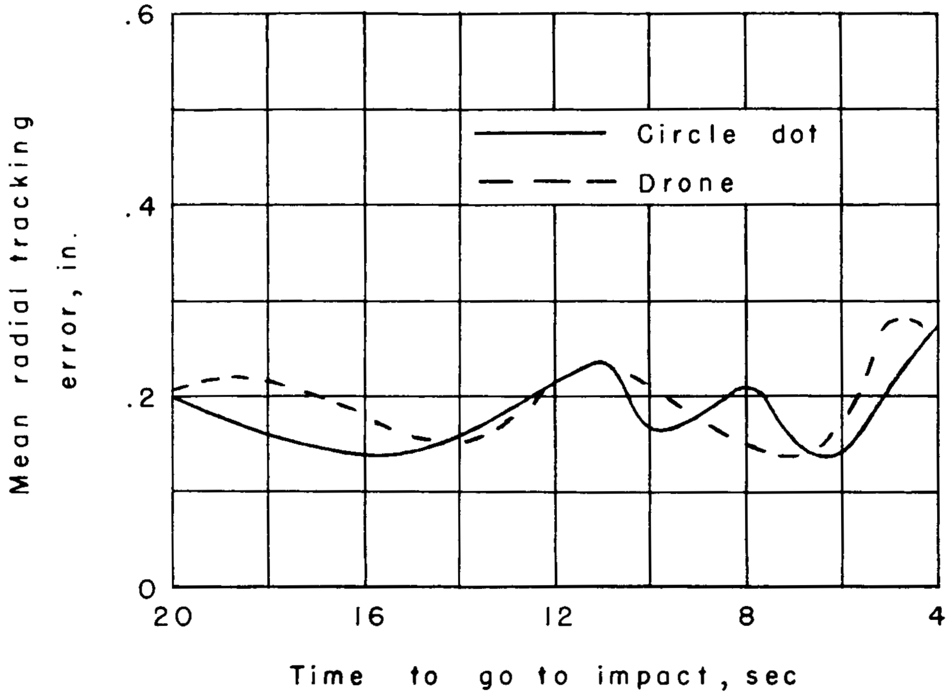


Figure 13.- Time histories of mean radial tracking error during the lead-collision attacks in flight; pilot A.

A-324

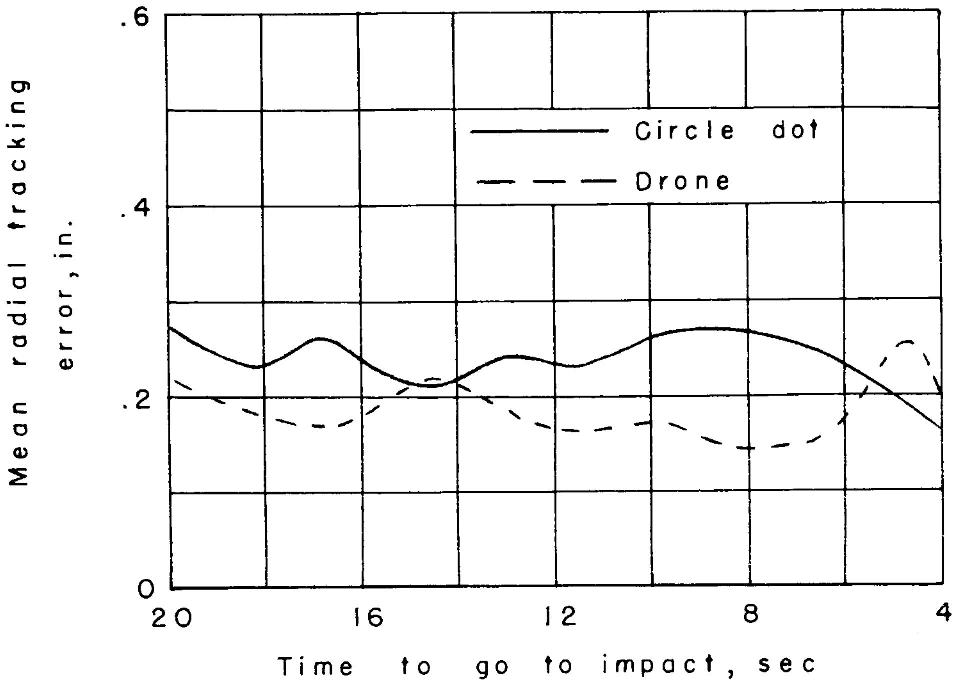


Figure 14.- Time histories of mean radial tracking error during the lead-collision attacks in flight; pilot B.

A-324

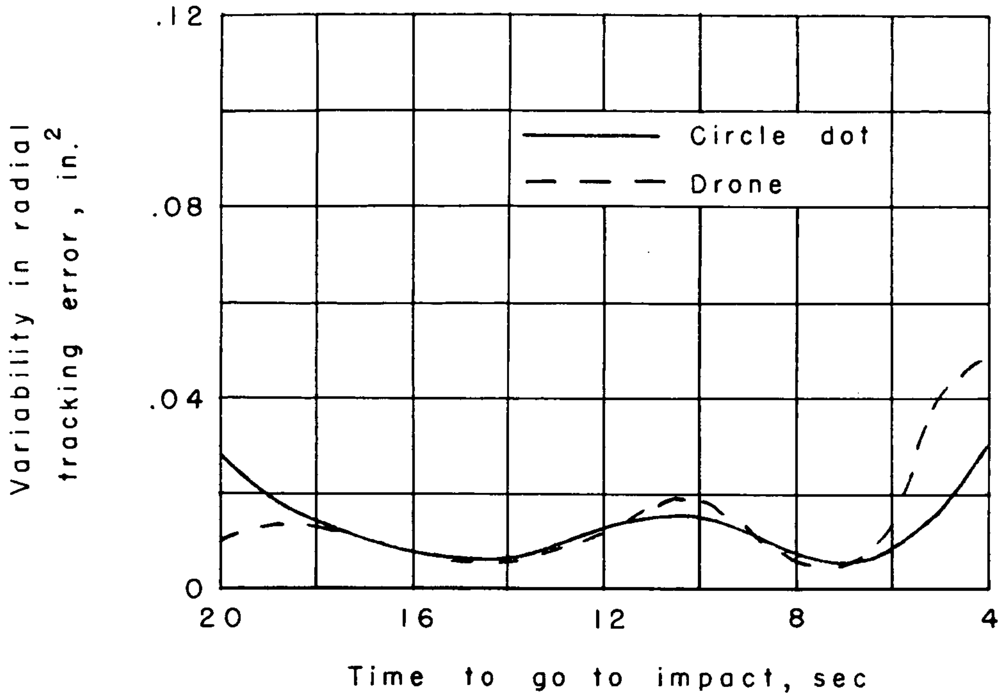


Figure 15.- Time histories of variability in radial tracking error during the lead-collision attacks in flight; pilot A.

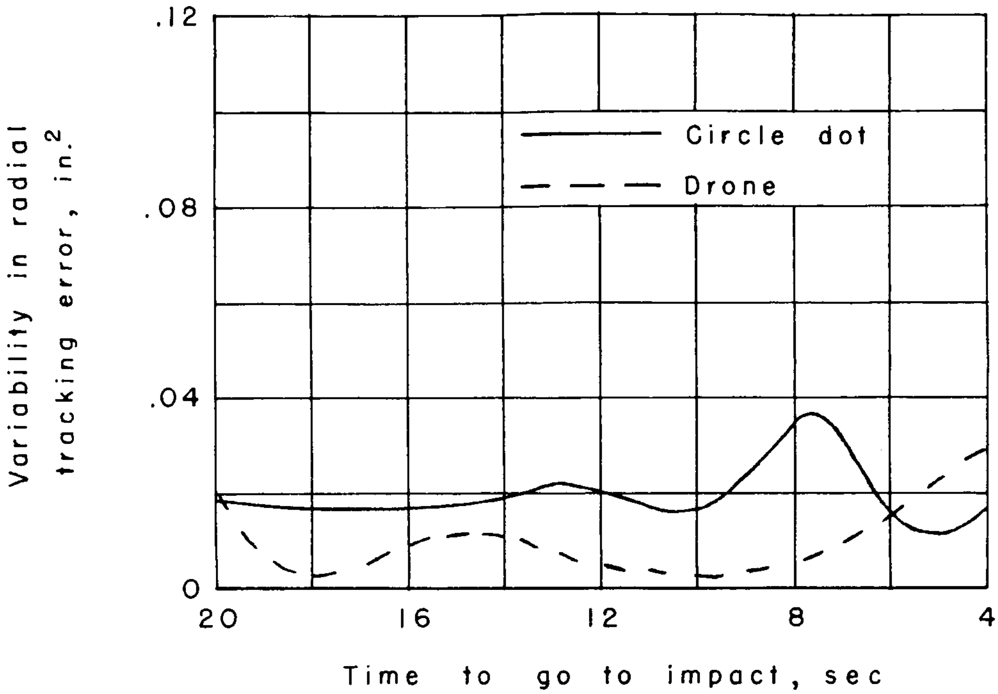


Figure 16.- Time histories of variability in radial tracking error during the lead-collision attacks in flight; pilot B.

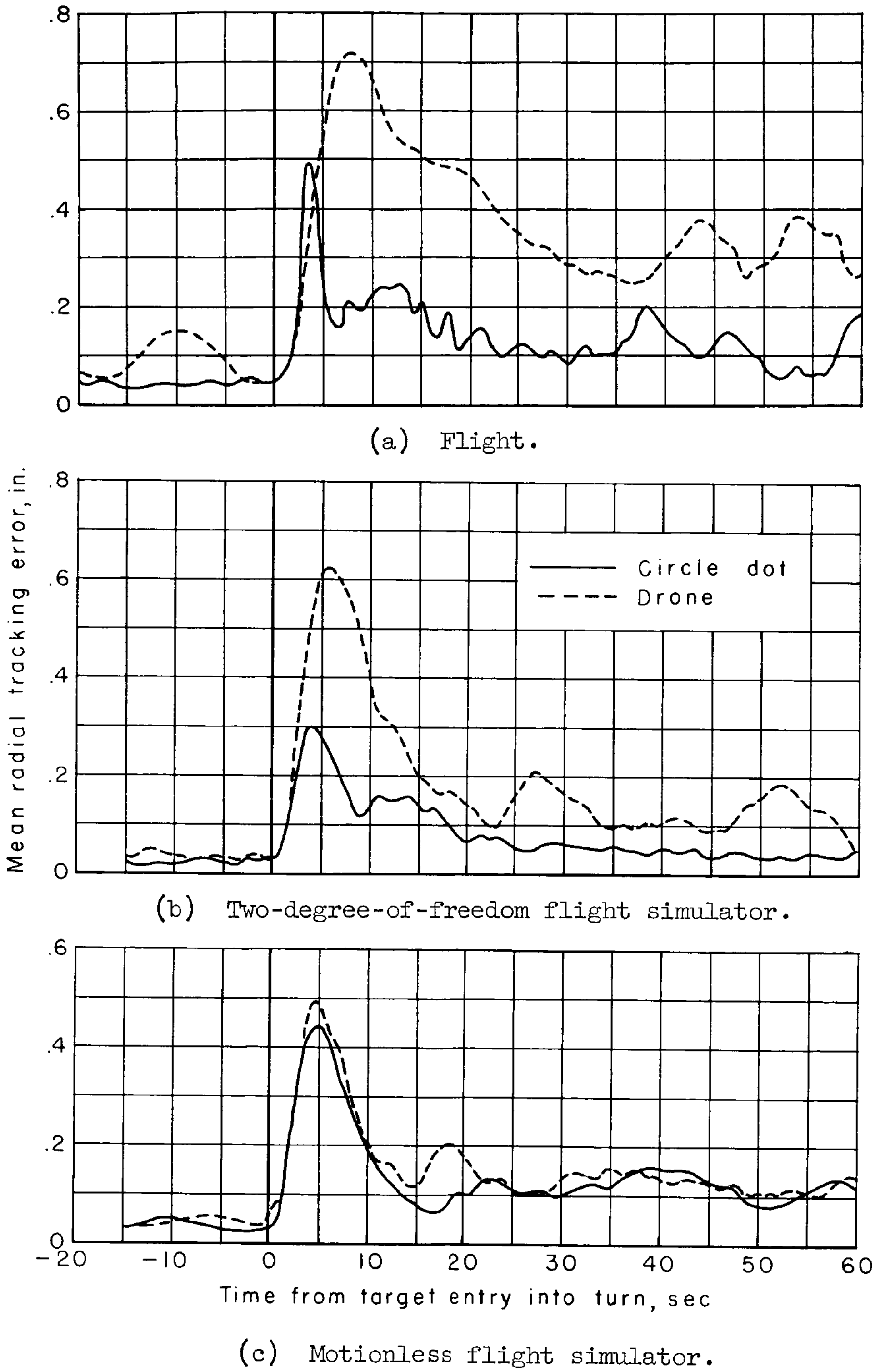


Figure 17.- Time histories of mean radial tracking error during the pursuit task in the three test environments; pilot A.

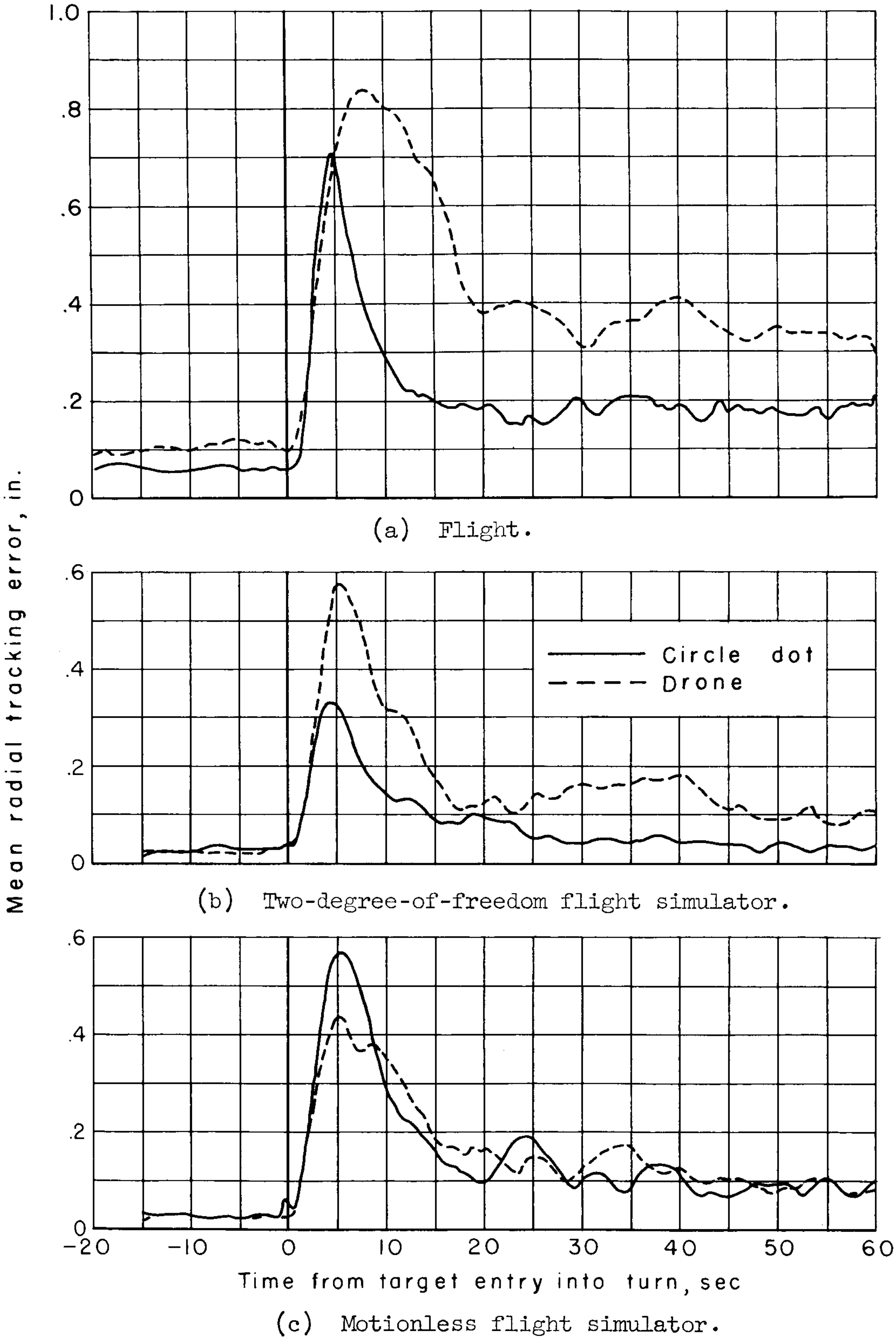
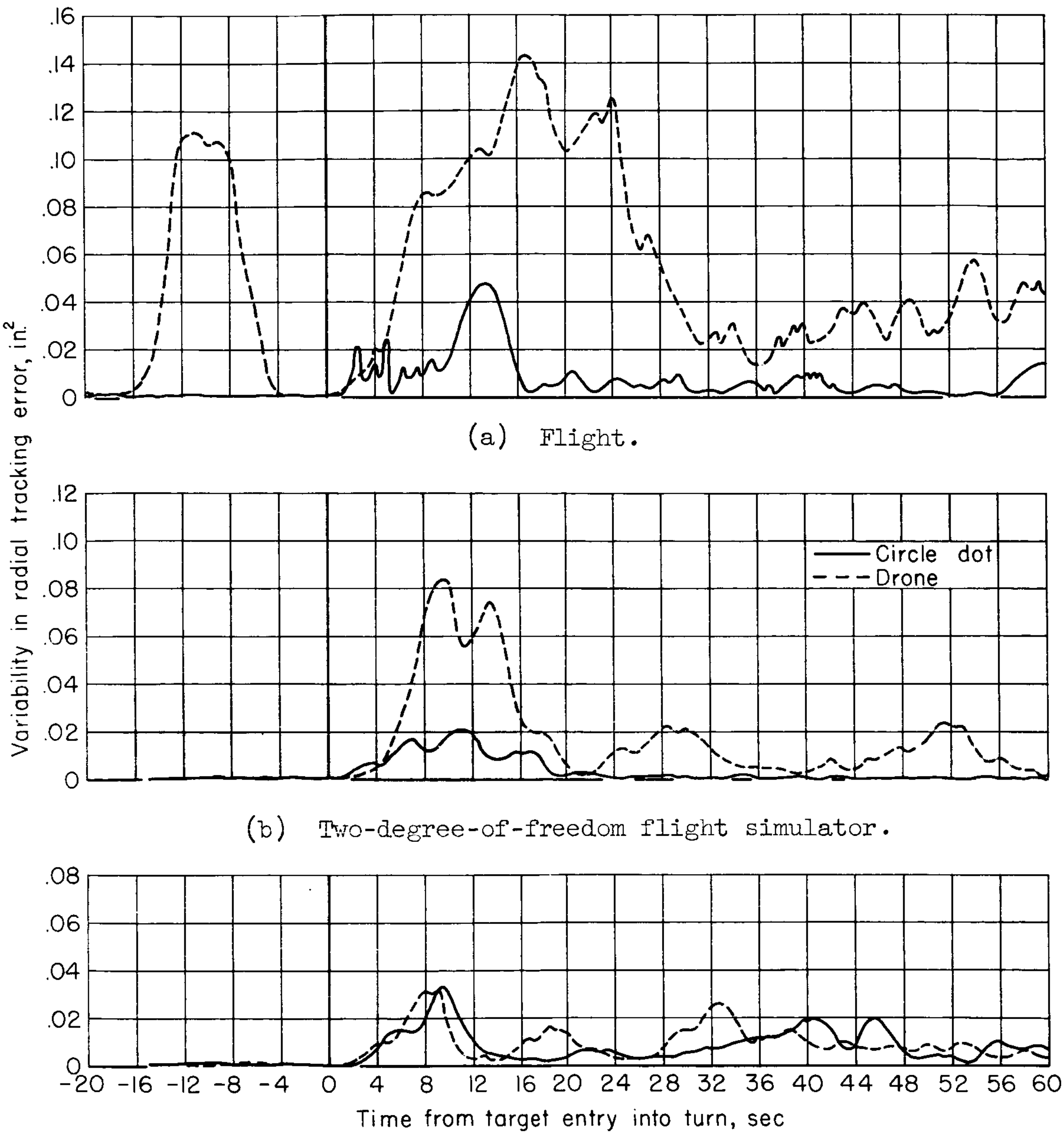


Figure 18.- Time histories of mean radial tracking error during the pursuit task in the three test environments; pilot B.



(c) Motionless flight simulator.

Figure 19.- Time histories of variability in radial tracking error during the pursuit task in the three test environments; pilot A.

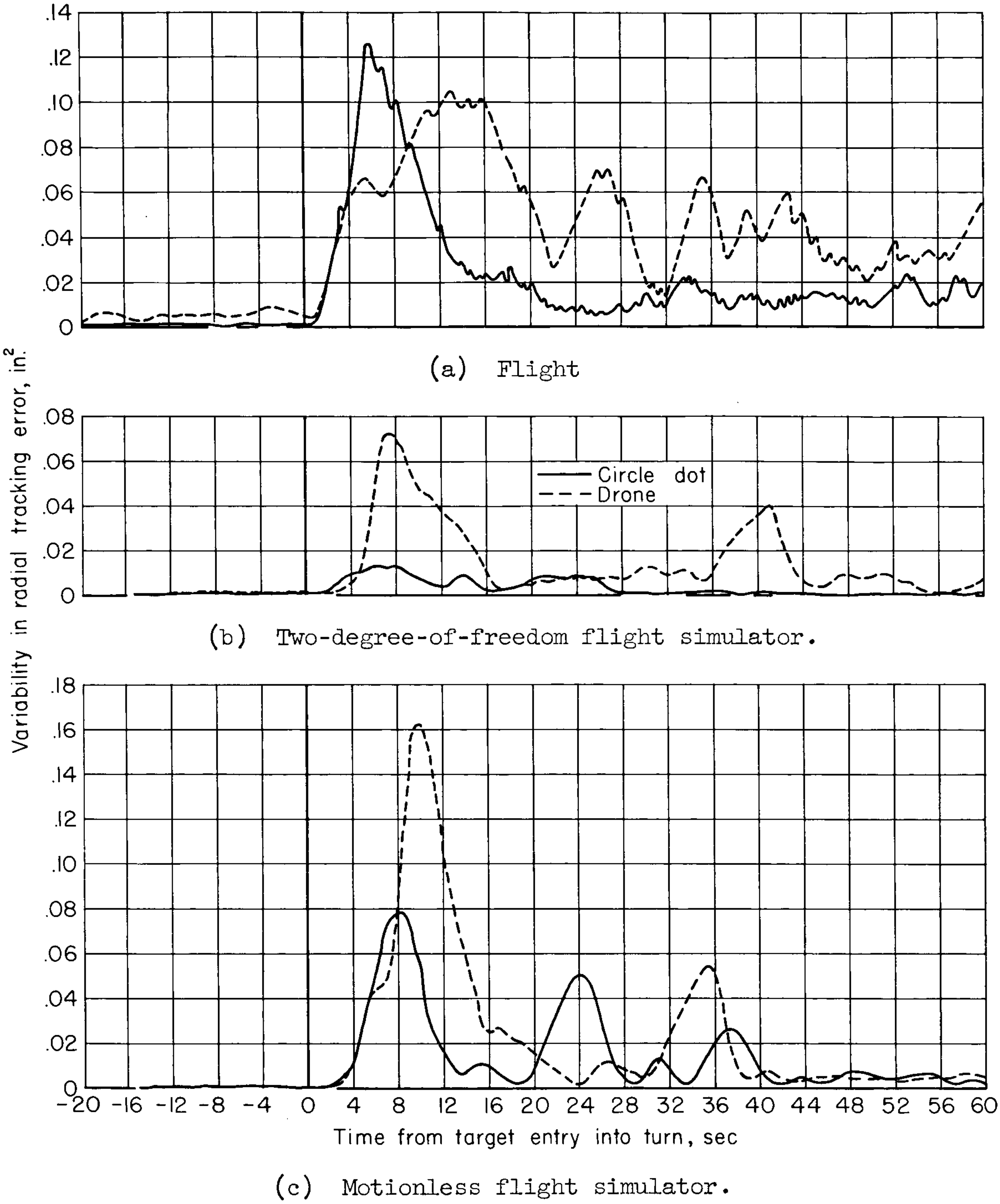
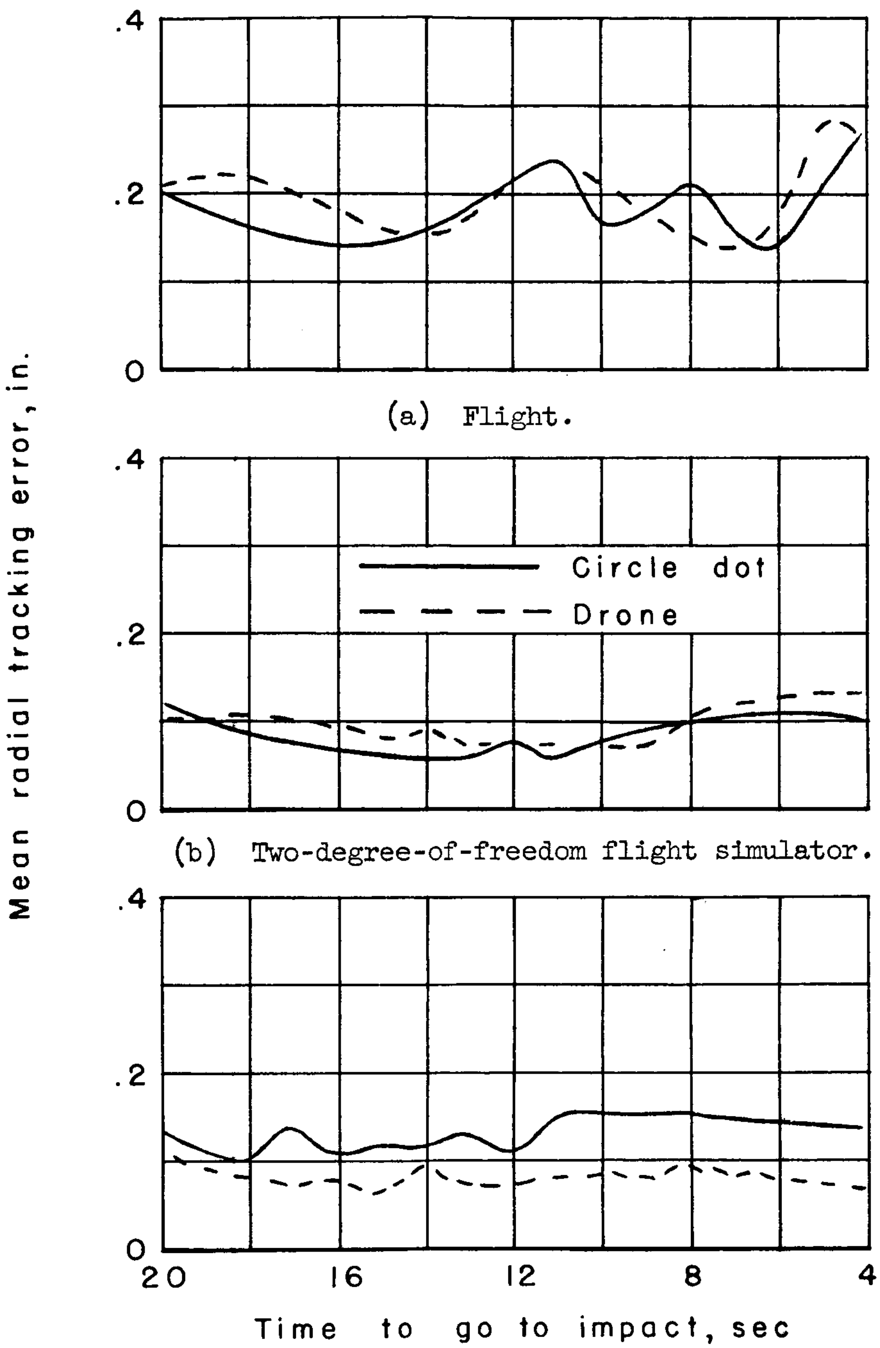


Figure 20.- Time histories of variability in radial tracking error during the pursuit task in the three test environments; pilot B.

A-324

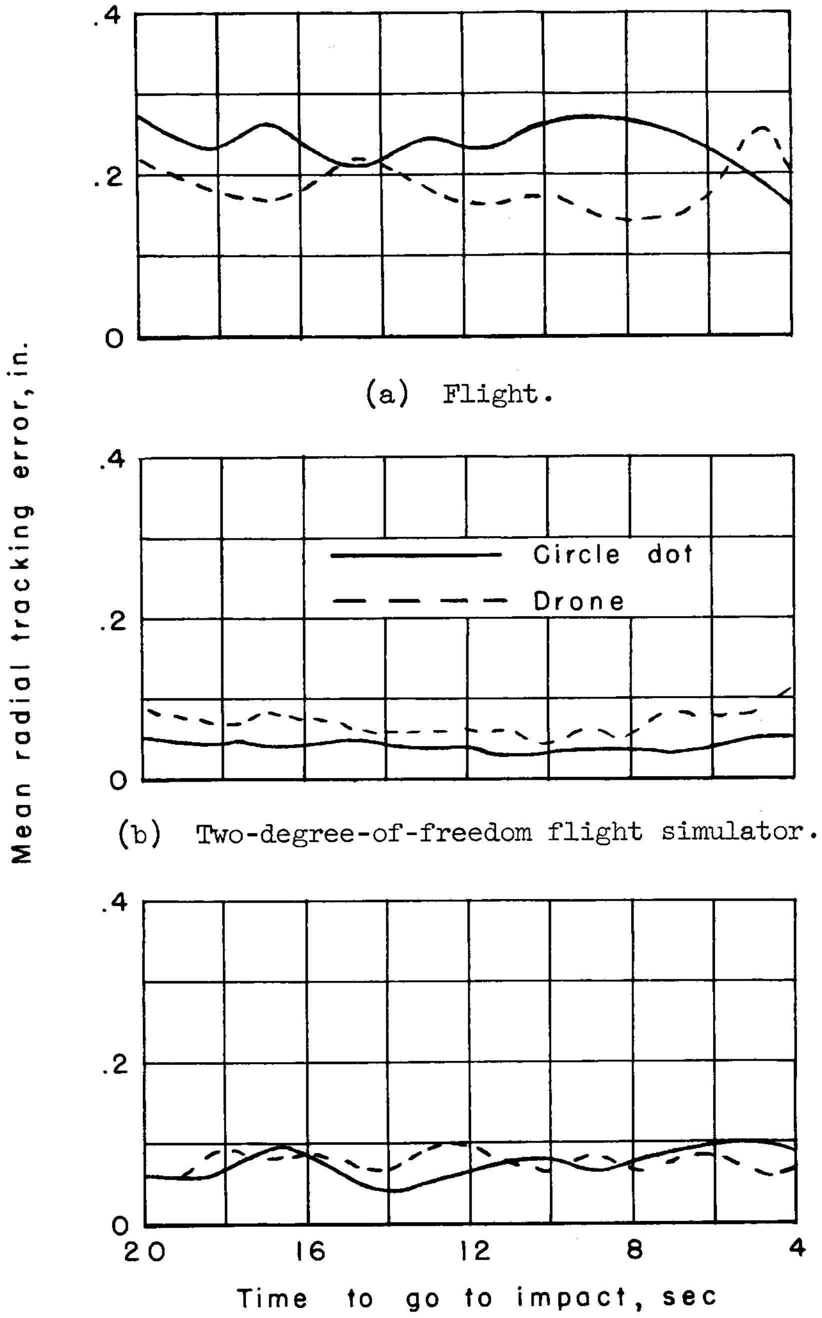


(a) Flight.

(b) Two-degree-of-freedom flight simulator.

(c) Motionless flight simulator.

Figure 21.- Time histories of mean radial tracking error during the lead-collision attacks in the three test environments; pilot A.



(c) Motionless flight simulator.

Figure 22.- Time histories of mean radial tracking error during the lead-collision attacks in the three test environments; pilot B.